DESCRIPTION

Permanent Magnet Electric Motor

Technical Field

The present invention relates to improvements in a permanent magnet electric motor to reduce a cogging torque.

Background Art

A permanent magnet electric motor produces a rotational variation called a cogging torque. The cogging torque generates a vibration or noise to cause the control performance of electric motor to be degraded. Therefore, a method for reducing the cogging torque was disclosed in JP-A-4-21330. According to this patent, to remove two frequency components of the cogging torque, permanent magnets are arranged at four stages in the axial direction of a rotor iron core and shifted in the circumferential direction of the rotor iron core to give rise to a skew effect, so that a plurality of permanent magnets are dislocated in the circumferential direction depending on an axial position of the rotor, namely, arranged on the surface of the rotor iron core at a skew angle (hereinafter referred to a stage skew angle).

A theoretically calculated angle (hereinafter referred to as a theoretical angle θt) for the stage skew angle is employed. The theoretical angle θt1 for a fundamental wave component of

the cogging torque is given by

$$\theta t1 = (360°/\text{least common multiple of the number of stator magnetic poles and the number of rotor magnetic poles})/2 \quad ..(3)$$

Further, the theoretical angle $\theta t2$ for the second order higher harmonic wave component of the cogging torque is half $\theta t1$.

However, if the theoretical angle of stage skew angle is actually applied to the permanent magnet electric motor, a reduced cogging torque is possibly less sufficient. Its reason is that an axial leakage flux occurs due to employment of the stage skew, but the influence of a magnetic saturation with the leakage flux is not considered. The leakage flux causing the cogging torque may occur at the stage portion of the permanent magnet and inside the rotor iron core, but the leakage flux inside the stator iron core is a main cause of the cogging torque. Therefore, there was a problem that the cogging torque was not fully reduced because the theoretical angle was employed for the skew angle of the rotor.

Also, the constitution of the rotor was complex to remove two frequency components of the cogging torque.

Disclosure of the Invention

The present invention has been achieved to solve the above-mentioned problems, and it is an object of the invention to provide a permanent magnet electric motor in which two

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frequency components of the cogging torque are removed and the rotor has a simple constitution.

Also, it is another object of the invention to provide a permanent magnet electric motor in which the cogging torque is lower than at the theoretical angle employed for the stage skew angle.

A permanent magnet electric motor according to this invention is characterized by comprising a rotor provided with two stages of permanent magnets in the axial direction on an outer circumferential face of a rotor iron core, and having a shaft shifted by a first stage skew angle θr in electrical angle to decrease a first frequency component of cogging torque in the circumferential direction of the rotor iron core between two stages of the permanent magnets, a stator iron core of cylindrical shape provided with the stator winding for producing a rotating magnetic field causing the rotor to be rotated, and a stator dividing the stator iron core in plural blocks in the axial direction, and shifted by a second stage skew angle θs in electrical angle to decrease a second frequency component of the cogging torque in the circumferential direction of the stator iron core.

This permanent magnet electric motor has an advantage that two frequency components of the cogging torque are decreased and the rotor has a simple construction, because the rotor and the stator are provided with the first and second stage skews.

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The permanent magnet electric motor according to another invention is characterized in that θt = (360°/least common multiple of the number of stator magnetic poles and the number of rotor magnetic poles)/2, $\theta t < \theta r < (700 \times 10^3/Lc + \theta t)$, where the axial length of the stator iron core is Lc (m), and the theoretical angle of the first stage skew angle is an electrical angle θt (°).

This permanent magnet electric motor has an advantage that two frequency components of the cogging torque are lower than at the theoretical angle employed for the stage skew angle, and the rotor has a simple construction.

The permanent magnet electric motor according to another invention is characterized in that the stator has the stator iron core divided into the first, second and third stator blocks in the axial direction, wherein the second stage skew angle θs is provided between the first stator block and the second stator block, and between the second stator block and the third stator block.

This permanent magnet electric motor has an advantage that the stator has a simple construction.

The permanent magnet electric motor according to another invention is characterized in that a clearance Lcg is provided between the first stator block and the second stator block, and between the second stator block and the third stator block, such that the inequality $0 < Lcg < 2.2gm$ holds, where gm is a gap between the stator and the rotor.

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This permanent magnet electric motor has an advantage that the induced voltage constant ratio is not reduced by decreasing the leakage flux in the axial direction at the top end of the stator magnetic pole teeth owing to a clearance Lcg.

Brief Description of the Drawings

Fig. 1 is a side cross-sectional view of a permanent magnet electric motor according to one embodiment of the present invention.

Fig. 2 is a perspective view of a rotor in the permanent magnet electric motor as shown in Fig. 1.

Figs. 3A and 3B are plan views of the rotor in the permanent magnet electric motor as shown in Fig. 1.

Fig. 4 is a perspective view of a stator in the permanent magnet electric motor as shown in Fig. 1.

Figs. 5A-5C are partial plan views of an upper stage stator block, a middle stage stator block, and a lower stage stator block as shown in Fig. 4.

Fig. 6 is a curve showing the magnetic characteristics of a stator iron core and a rotor iron core in the permanent magnet electric motor as shown in Fig. 1.

Fig. 7 is a characteristic curve showing the fundamental wave component of cogging torque and the rotor skew angle obtained as a result from the three dimensional magnetic field analysis for the permanent magnet electric motor as shown in

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Fig. 1.

Fig. 8 is a characteristic curve showing the second order higher harmonic wave component of cogging torque and the rotor skew angle obtained as a result from the three dimensional magnetic field analysis for the permanent magnet electric motor as shown in Fig. 1.

Figs. 9A-9D are characteristic curves showing the relationship between the rotor skew angle and the cogging torque by changing the axial length of the stator in the permanent magnet electric motor as shown in Fig. 1.

Fig. 10 is a characteristic curve showing the relationship between the induced voltage constant ratio and Lcg/gm for a permanent magnet electric motor according to another embodiment of the invention.

Fig. 11 is a side cross-sectional view of the permanent magnet electric motor according to another embodiment of the invention.

Fig. 12 is a side cross-sectional view of a permanent magnet electric motor according to a further embodiment of the invention.

Best Mode for Carrying Out the Invention

Embodiment 1

Referring to Figs. 1 to 5, an embodiment 1 of the present invention will be described below. Fig. 1 is a side

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cross-sectional view of a permanent magnet electric motor according to the embodiment 1 of the invention. Fig. 2 is a perspective view of a rotor in the permanent magnet electric motor as shown in Fig. 1. Figs. 3A and 3B are plan views of the rotor in the permanent magnet electric motor as shown in Fig. 1. Fig. 4 is a perspective view of a stator in the permanent magnet electric motor as shown in Fig. 1. Figs. 5A-5C are plan views of an upper stage stator block, a middle stage stator block, and a lower stage stator block as shown in Fig. 4.

In Figs. 1 to 5, the permanent magnet electric motor 10 is formed of an electromagnetic steel plate that is punched with the stator magnetic pole teeth 22t connected to a thin connecting portion, and comprises a stator iron core 21 of cylindrical shape, a stator 20 with 12 magnetic poles formed by winding a plurality of stator windings 24 around the inner circumference of the stator iron core 21, and a rotor 30 with eight magnetic poles having a rotor iron core 32 rotatable around the center of the stator 20 and making a gap gm (m) with the stator 20, whereby the rotor 30 is rotated around a rotational shaft under a rotating magnetic field by energizing the stator windings 24.

In Figs. 2 and 3, the rotor 30 has eight magnetic poles, and comprises two rotor iron cores 32 and 34 of cylindrical shape which are formed of an electromagnetic steel plate at two stages, an upper stage permanent magnet 32m and a lower

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stage permanent magnet 34m which are arcuate and bonded in which N pole and S pole alternately arranged on the outer circumferential face of the rotor iron cores 32 and 34. To remove a fundamental wave component of cogging torque, the lower stage permanent magnet 34m is circumferentially shifted by an angle θr in electrical angle with respect to the line O-m connecting the line m passing through the center of the upper stage permanent magnet 32m and the center O of the rotor iron core, thereby forming a rotor skew angle θr (electrical angle) as the first stage skew angle.

In Fig. 4, the stator 21 is composed of an upper stage stator block 22 as the first stator block, a middle stage stator block 24 as the second stator block, and a lower stage stator block 26 as the third stator block, which are disposed in the axial direction, with the axial length being Lc. Further, the stator 21 comprises two filling stator blocks 22i having the axial length Lcg inserted between the upper stage stator block 22 and the middle stage stator block 24, and between the middle stage stator block 24 and the lower stage stator block 26, in which the middle stage stator block 24 and the lower stage stator block 26 are circumferentially shifted by a stator skew angle θs (electrical angle) of 15° as a second stage skew angle corresponding to the theoretical angle to remove the second order higher harmonic wave component of cogging torque.

And the upper stage stator block 22, the middle stage

stator block 24, and the lower stage stator block 26 are formed in the axial length (Lc/4-Lcg/2), (Lc/2-Lcg) and (Lc/4-Lcg/2), respectively.

In Figs. 5A-5C, to implement the shift by the stator skew angle θs, the upper stage stator block 22 and the lower stage stator block 26 are shifted by angle $\theta s/2$ counterclockwise from the central line S0 of slot, the filling stator block 22i is matched with the central line S0 of slot, and the middle stage stator block 24 is shifted by angle $\theta s/2$ clockwise from the central line S0 of slot.

The stator 20 is provided with a clearance Lcg (m) in the axial direction of the stator between the end portions of the upper stage stator block 22 and the middle stage stator block 24 by inserting the filling stator block 22i. Similarly, the stator 20 is provided with a clearance Lcg (m) in the axial direction of the stator 20 between the end portions of the middle stage stator block 24 and the lower stage stator block 26. There is a relation 0<Lcg<2.2gm between the gap gm and clearance Lcg.

Referring to Figs. 6 to 9, the reason why the skew angle is deviated from the theoretical value is explained below. Fig. 6 is a BH characteristic curve of the stator iron core 20 and the rotor iron core that are employed for analysis. In Fig. 6, the magnetic flux density ratio in the longitudinal axis indicates the ratio of magnetic flux density to the reference value that is a saturation magnetic flux density of the material

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of magnetic characteristic A, and the magnetizing force is indicated in the transverse axis. Magnetic characteristic A shows an instance where there is no influence of working. Magnetic characteristic B shows an instance where the magnetic flux density ratio is reduced by about 20% in the vicinity of a magnetizing force H = 1000A/m as compared with the magnetic characteristic A, corresponding to the permanent magnet electric motor 10 that is actually employed. This is because the permanent magnet electric motor 10 is degraded in the characteristics during the process of working the stator 20 and the rotor 30.

Referring to Figs. 7 and 8, the relationship between the cogging torque and the rotor skew angle θr and stator skew angle θs in the cases of the magnetic characteristics A and B is explained below. Fig. 7 is a characteristic curve showing the results from the three dimensional magnetic field analysis for the fundamental wave component of cogging torque in the permanent magnet electric motor 10. Likewise, Fig. 8 is a characteristic curve showing the results from the three dimensional magnetic field analysis for the second order higher harmonic wave component of cogging torque.

In Figs. 7 and 8, for the magnetic characteristics A and B of the stator iron core 20, the longitudinal axis indicates how the cogging torque of the rotor 30 or the stator 20 with stage skew falls, when the cogging torque without stage skew

is supposed to be 1, and the transverse axis indicates the skew angle (electrical angle) θr, θs.

In Fig. 7, for the fundamental wave component of cogging torque, the rotor skew angle θr at which the cogging torque ratio is minimum is increased as the magnetic characteristic is degraded from A to B. This is because a leakage flux occurs in the axial direction inside the stator iron core 21 by employing the stage skew.

The rotor skew angle θr is greater than the theoretical angle 30° at which the cogging torque is minimum, as the magnetic characteristic of the stator iron core is degraded. In the magnetic characteristic B, when the rotor skew angle θr is the theoretical angle of 30°, the cogging torque ratio at point fc is about 0.18. When the rotor skew angle θr is beyond the theoretical angle of 30° and the cogging torque ratio is less than or equal to 0.18 at point fc, the rotor skew angle θr is reduced below the stage skew angle θr (about 37°) that is the maximum value at point fc', whereby the fundamental wave component of cogging torque is lower than at the theoretical angle 30°.

In Fig. 8, for the second order higher harmonic wave component of cogging torque, when the stator skew angle θs is the theoretical angle θt, the cogging torque ratio is minimum at the electrical angles of 15° and 45°. This is because the second order higher harmonic wave component of cogging torque

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is less susceptible to the axial leakage magnetic flux or magnetic saturation.

Figs. 9A-9D shows the results of the three dimensional analysis for the fundamental wave component of cogging torque when the axial length Lc of the stator iron core is changed, on the basis of the rotor skew angle θr=0, namely, the cogging torque in the rotor 30 without forming the skew. The rotor skew angle θr at which the cogging torque is minimum is different from the theoretical angle, because an axial leakage flux occurs inside the stator iron core 21k as the stator 20 is worked and degraded in a portion of the stage skew. The cogging torque based on the axial leakage flux is almost constant without regard to the axial length Lc, because the axial leakage flux occurs near the stage skew portion. Accordingly, when the axial length Lc of the stator iron core 21 is small, the rotor skew angle θr must be greater than the theoretical angle θt, because the axial leakage flux has a relatively great influence. On the contrary, when the axial length Lc of the stator iron core 21 is large, the rotor skew angle θr is closer to the theoretical angle θs, because the axial leakage flux has a relatively small influence.

In Fig. 9A, when the axial length Lc of the stator 20 is Lc=40×10⁻³(m), the rotor skew angle θr is greater than the theoretical angle θt=30° at point fc, the minimum value of the cogging torque is 40.1°, and the rotor skew angle θr at point

fc' at which the cogging torque is equal to the theoretical angle $\theta r=30°$ is 47.5°. That is, when the rotor skew angle θr is greater than the theoretical angle $\theta t=30°$, and smaller than 47.5°, the cogging torque is reduced as compared with when the rotor skew angle is set at the theoretical angle θt.

In Fig. 9B, when the axial length Lc of the stator 20 is $Lc=80 \times 10^{-3}$ (m), the rotor skew angle θr is greater than the theoretical angle $\theta t=30°$ at point fc, the minimum value of the cogging torque is 33.8°, and the rotor skew angle θr at point fc' at which the cogging torque is equal to the theoretical angle $\theta r=30°$ is 38.8°. That is, when the rotor skew angle θr is greater than the theoretical angle $\theta t=30°$, and smaller than 38.8°, the cogging torque is reduced as compared with when the rotor skew angle is set at the theoretical angle θt.

In Fig. 9C, when the axial length Lc of the stator 20 is $Lc=100 \times 10^{-3}$ (m), the rotor skew angle θr is greater than the theoretical angle $\theta t=30°$ at point fc, the minimum value of the cogging torque is 33°, and the rotor skew angle θr at point fc' at which the cogging torque is equal to the theoretical angle $\theta r=30°$ is 37.0°. That is, when the rotor skew angle θr is greater than the theoretical angle $\theta t=30°$, and smaller than 37.0°, the cogging torque is reduced as compared with when the rotor skew angle is set at the theoretical angle θt.

In Fig. 9D, when the axial length Lc of the stator 20 is $Lc=120 \times 10^{-3}$ (m), the rotor skew angle θr is greater than the

theoretical angle $\theta t=30°$ at point fc, the minimum value of the cogging torque is 32°, and the rotor skew angle θr at point fc' at which the cogging torque is equal to the theoretical angle $\theta t=30°$ is 35.8°. That is, when the rotor skew angle θr is greater than the theoretical angle $\theta t=30°$, and smaller than 35.8°, the cogging torque is reduced as compared with when the rotor skew angle is set at the theoretical angle θt.

From the above discussion, the maximum value $\theta r max$ of the rotor skew angle at which the cogging torque is equal to the theoretical angle $\theta t=30°$ is given by the following expression from the empirical formula based on the analysis results.

$$\theta r max = 700 \times 10^3/Lc + \theta t \qquad \qquad .. \quad (4)$$

Accordingly, to reduce the cogging torque less than at the theoretical angle $\theta t=30°$ by setting the rotor skew angle θr, it is necessary to satisfy the inequality $\theta t < \theta r < (700 \times 10^3/Lc + \theta t)$.

In the permanent magnet electric motor 10, these characteristic curves show the three dimensional analysis results for the relationship between the ratio Lcg/gm and the induced voltage constant ratio on the basis of the induced voltage constant ratio when the ratio Lcg/gm of the clearance Lcg at the top portion of the stator magnetic pole teeth to the rotor gap gm is zero.

In Fig. 10, the induced voltage constant ratio is increased, reaches the maximum value, and then decreased, as the ratio

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Lcg/gm is greater. Thereby, to obtain the induced voltage constant ratio at which the ratio Lcg/gm is equal to zero, it is necessary to reduce the ratio Lcg/gm below 2.2.

Thereby, the clearance Lcg at the top portion of the stator magnetic pole teeth to enhance the induced voltage constant is in a range 0<Lcg<2.2gm.

Embodiment 2

Another embodiment of the present invention will be described referring to Fig. 11. Fig 11 is a perspective view of the stator according to another embodiment.

In the above embodiment 1, the fundamental wave component of cogging torque is reduced by providing the rotor iron cores 32 and 34 with the rotor skew angle θr, and the second order higher harmonic wave component of cogging torque is reduced by providing the stator iron cores 22, 24 and 26 with the stator skew angle θs.

In this embodiment, the rotor 30 is the same as in the embodiment 1, but the stator 120 is divided into four stator iron cores 122, 124, 126 and 128, whereby the second order higher harmonic wave component of cogging torque is reduced by providing the stator skew angle θs.

The stage skew angle between the stator iron core 122 and the top portion of stator magnetic pole teeth in the stator iron core 126 and between the stator iron core 124 and the top portion of the stator magnetic pole teeth in the stator iron

core 128 is zero, and the stator skew angle θs between the stator iron core 122 and the stator iron core 124 and between the stator iron core 126 and the stator iron core 128 is formed.

Embodiment 3

Referring to Fig. 12, another embodiment of the invention will be described below. Fig. 12 is a side cross-sectional view of a permanent magnet electric motor according to another embodiment of the invention.

In the above embodiments 1 and 2, the permanent magnet electric motor has the stator 20 disposed outside and the rotor 30 disposed inside the stator 20.

The permanent magnet electric motor 200 according to this embodiment has a rotor 230 disposed outside and a stator 220 disposed inside the rotor 230.

In the above embodiments 1 to 3, the rotor 30, 230 is formed with the skew angle θr for removing the fundamental wave component of cogging torque, and the stator 20, 220 is formed with the skew angle θs for removing the second order higher harmonic wave component of cogging torque. Conversely, the rotor 30, 230 may be formed with the skew angle θs for removing the second order higher harmonic wave component of cogging torque, and the stator 20, 220 may be formed with the skew angle θr for removing the fundamental wave component of cogging torque.

Industrial Applicability

As described above, the present invention is suitable for the purposes of the permanent magnet electric motor.